Fermi National Accelerator Laboratory
Particle Physics Division

Mechanical Department Engineering Note

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Project: *DES*

Project Internal Reference: *N/A*

Title: ***Updated Thermal Study of the DES 2k x 4k CCD Module V1 Design***

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Reviewer(s): ---

Key Words: *DES / CCD*

Abstract/Summary:

FEA studies of thermal deformation for various cases are reported. Reducing CCD thickness from 250 to 200 microns was observed to have virtually no effect on flatness, which was predicted to be about 5 microns at -100°C and 9 microns at -125°C. Changing foot material to AlN, a possibility for the V2 redesign, improved flatness significantly. A heat transfer study predicted a 2.3°C temperature variation within the module, with over half of that occurring in the Invar foot and most of the rest of the gradient appearing in the epoxy joints.

Applicable Codes: *N/A*

The DES module prototype was previously studied in Ref. 1. Since that time, the molybdenum foot material was changed to Invar and additional material property information has been utilized. Recent discussion regarding a potential change in sensor thickness has led to this overdue documenting of the latest quarter-section FEA analysis results. The following cases are reported here. The material properties assumed for these analyses are reported in the Appendix.

Thermal Distortion	Case 1	-100°C / 250 micron Si
	Case 2	-100°C / 200 micron Si
	Case 3	-125°C / 250 micron Si
	Case 4	-100°C / 200 micron Si / Invar switched to AlN

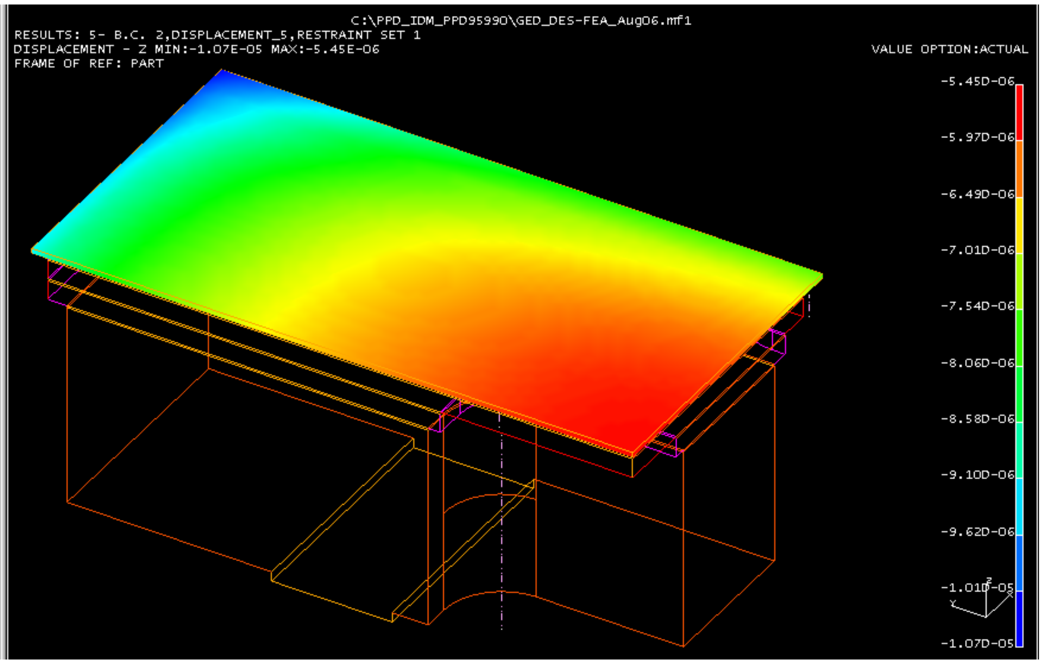
Temperature Distribution Heat Transfer Study

As previously reported, silicon flatness is critical for this project. The following requirements have been specified for the CCDs:

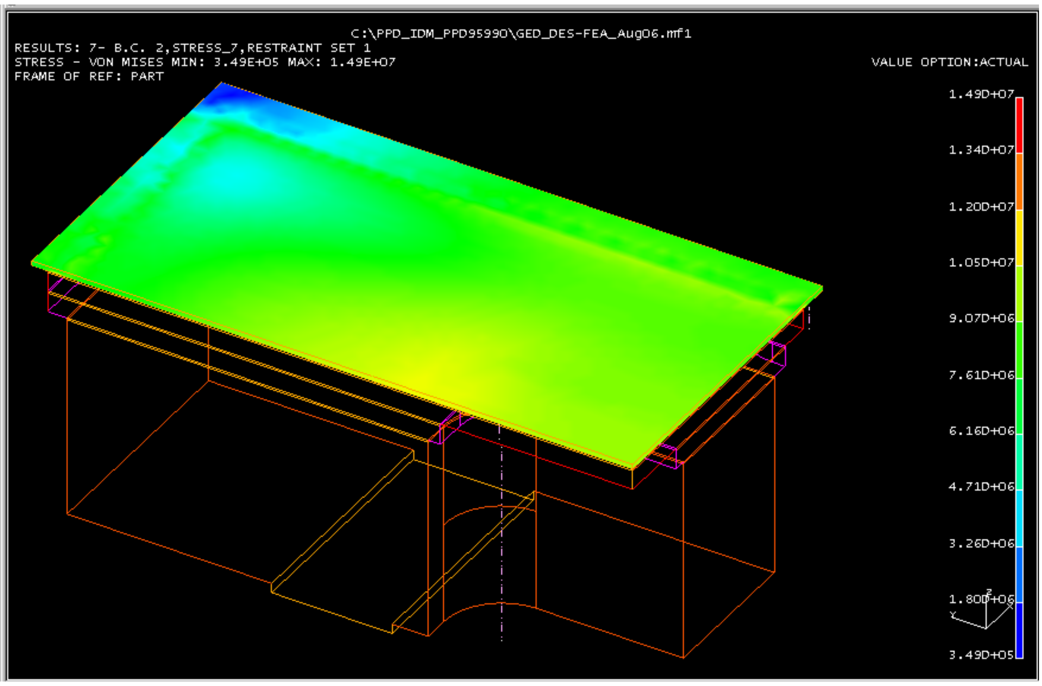
- On 1 cm^2 scales within a CCD, the mean height variation should be < 3 microns
- For adjacent 1 cm^2 areas within a CCD, the difference in mean heights should be < 10 microns
- Entire CCD surface within 25 microns of the mean focal plane

THERMAL DISTORTION CASE 1: -100°C / 250 micron Si

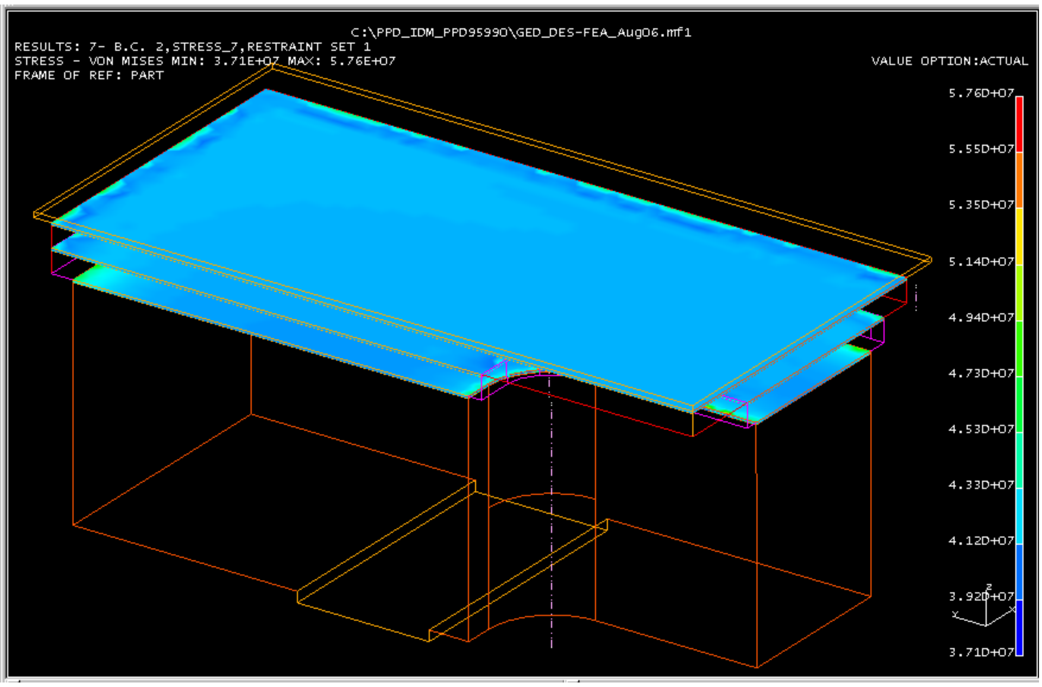
This case represents a reanalysis of the module configuration described in Ref. 1 but with an Invar36 foot and updated material property data. The Z deflection results are shown in the following image and predict a 5.2 micron thermally-induced variation over the surface of the CCD. The stresses found in the various materials is then shown and summarized.



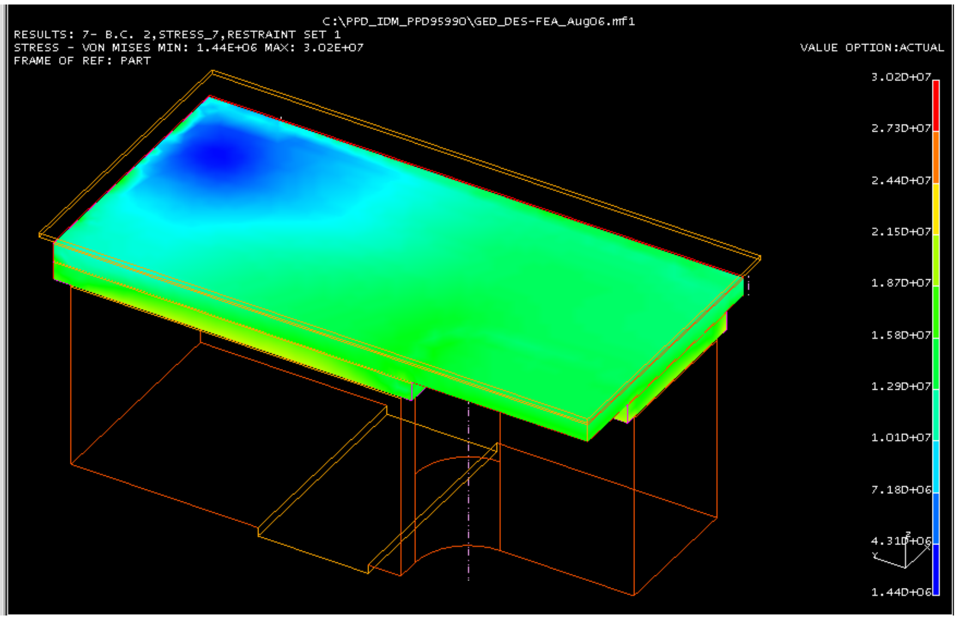
Case 1 Z Deflection Results
$\Delta Z = 10.7 - 5.5 = 5.2$ microns



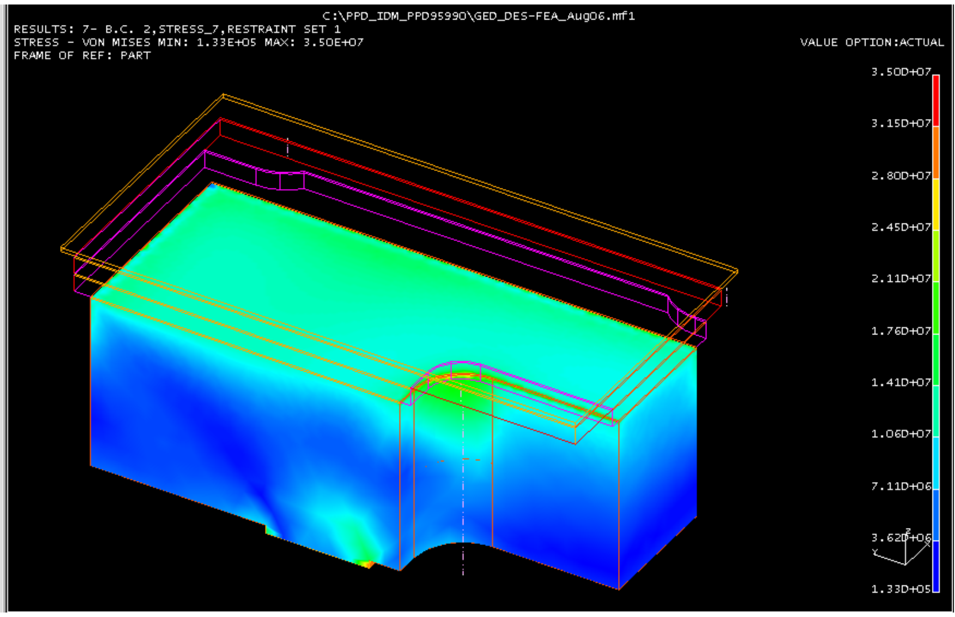
Case 1 Si Stress



Case 1 Epoxy Stress



Case 1 AlN Stress



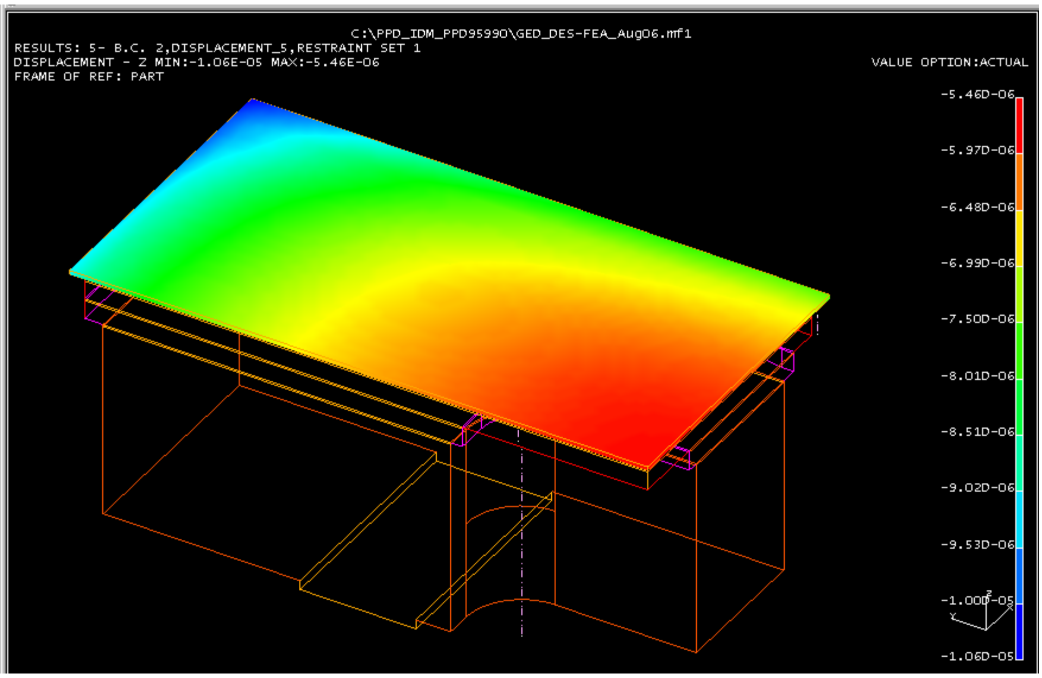
Case 1 Invar Stress

A comparison of the maximum stresses found indicates that the Si, AlN, and Invar are far from the limit stresses. Away from the mesh-edge effect areas, the epoxy stress is below the room temperature strength value and is also slightly below the maximum stress level tested at 150K, as discussed in the Appendix.

Silicon	14.9 MPa	(12% of stress limit)
Epoxy	57.6 (41 away from edge effect areas, 61% of 67 MPa)	
AlN	30.2	(11% of stress limit)
Invar	35.0	(7% of stress limit)

THERMAL DISTORTION CASE 2: -100°C / 200 micron Si

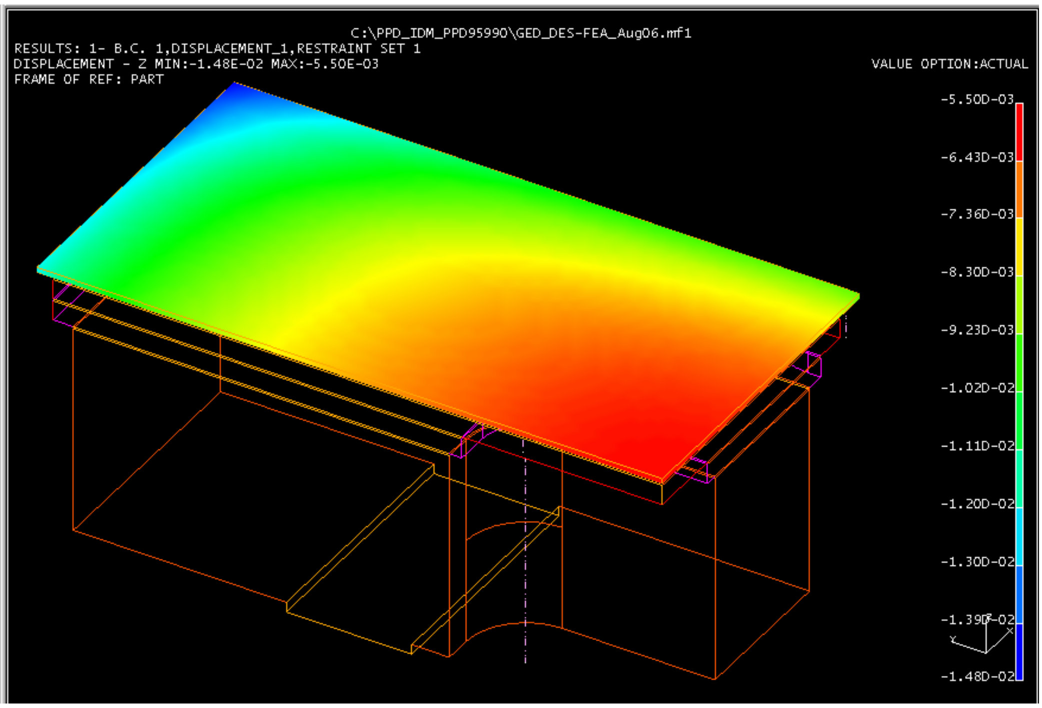
This case considers a thinner CCD sensor. The results indicate virtually no change in thermal deformation. Maximum stress in the silicon was found to be 15.3 MPa, which is 2.7% above the Case 1 results and still well below the limit.



Case 2 Z Deflection Results
ΔZ = 10.6 – 5.5 = 5.1 microns

THERMAL DISTORTION CASE 3: -125°C / 250 micron Si

This case has been run to investigate module behavior at a colder operating temperature. The 9.3 micron Z-deformation over the CCD is a 79% increase from the base case.



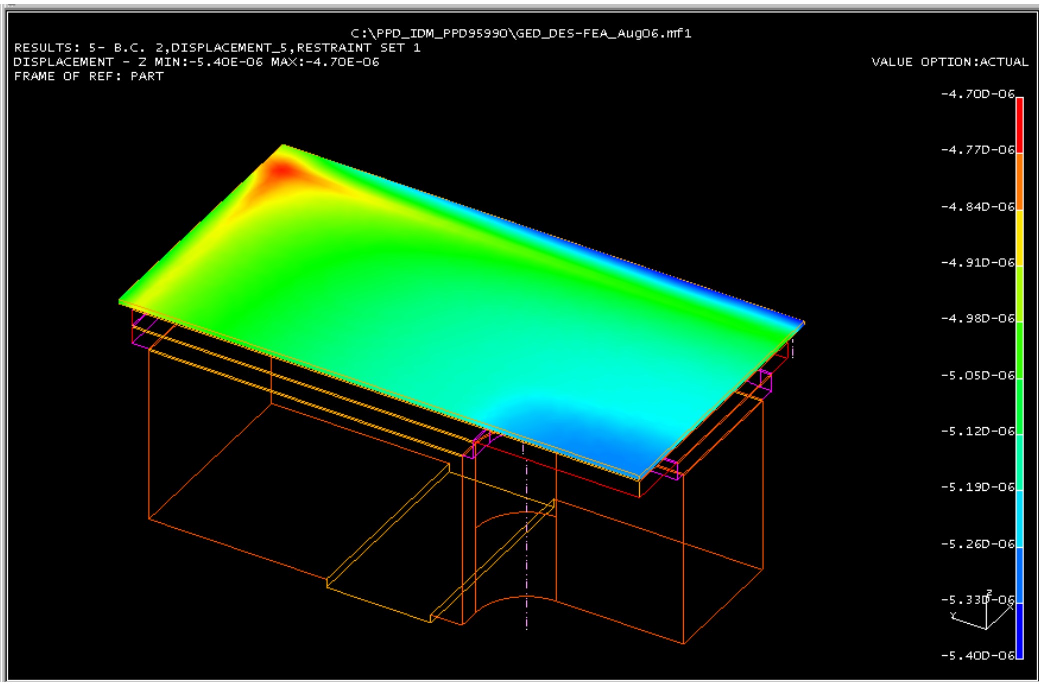
Case 3 Z Deflection Results
ΔZ = 14.8 – 5.5 = 9.3 microns

Individual stress result images are not shown here, but a summary of the results are shown below. Away from the mesh-edge effect areas, the epoxy stress is below the room temperature strength value, but is slightly above the maximum stress tested at 150K, as discussed in the Appendix.

Silicon	20.6 MPa	(17% of stress limit)
Epoxy	71.4 (49 away from edge effect areas, 73% of 67 MPa)	
AlN	48.1	(17%)
Invar	62.3	(13%)

THERMAL DISTORTION CASE 4:   -100°C / 250 micron Si / Foot Material Changed to AlN

Future design revisions (V2) to the module may include using AlN as a foot material. Although the configuration of such a foot (as yet undersigned) would be considerably different from the Invar foot, as a simple exploratory study the Invar material was changed to AlN for this run. Due to the very similar CTE between Si & AlN, the results indicate a very flat profile. This indicates that an all-AlN design should yield excellent flatness results. Issues of module mounting, position registration, etc., of course, would have to addressed for such a design.



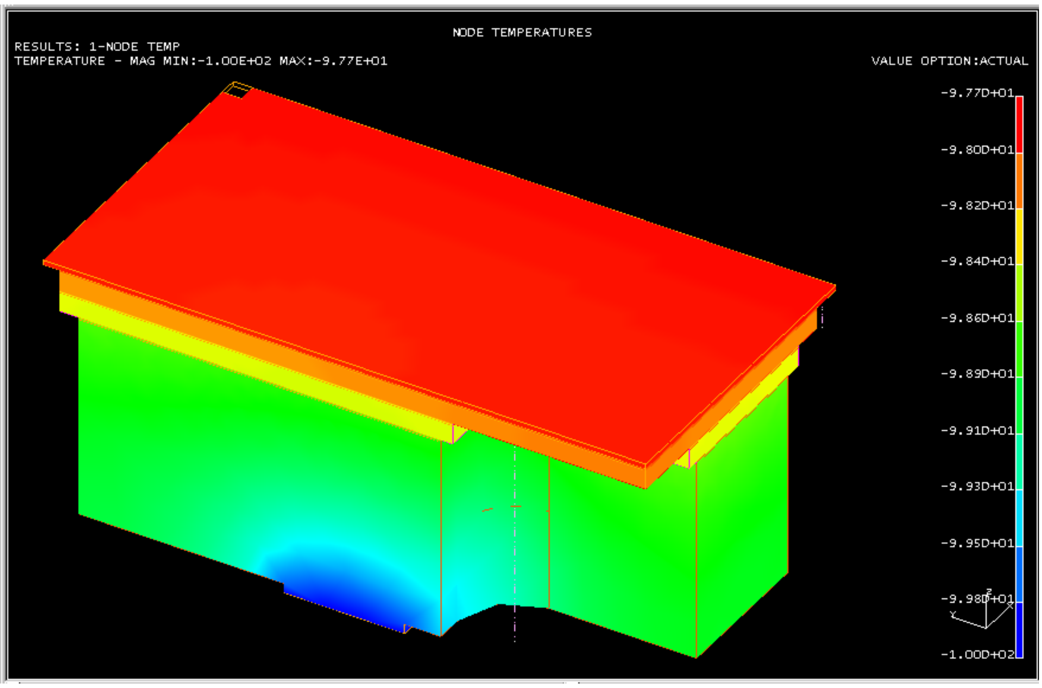
Case 4 Z Deflection Results
ΔZ = 5.4 – 4.7 = 0.7 microns

TEMPERATURE GRADIENT

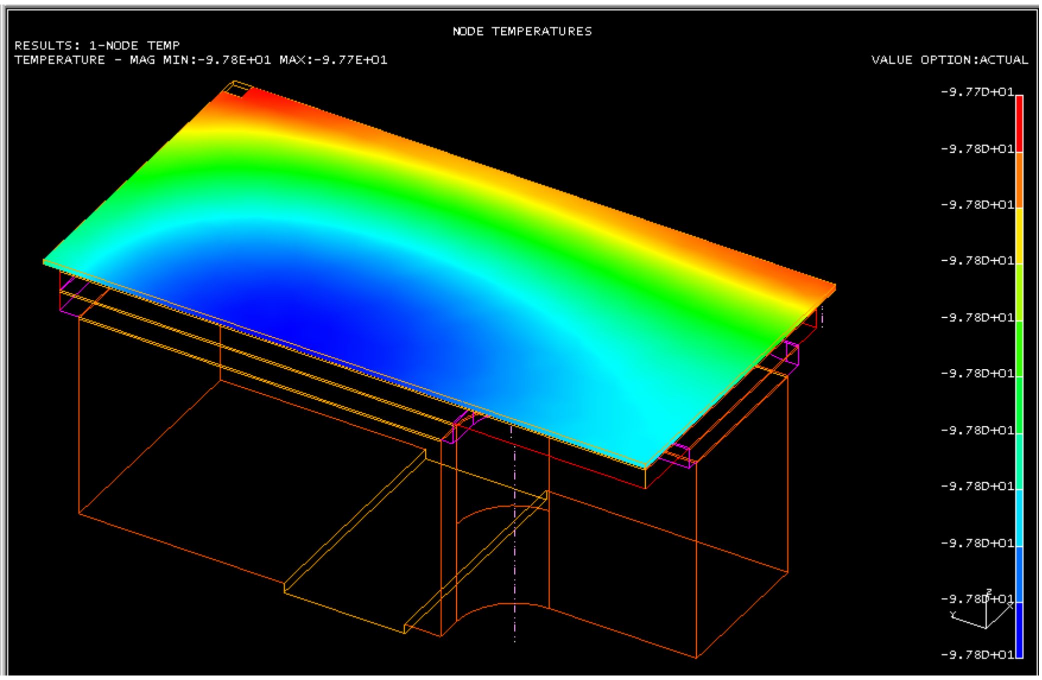
The temperature distribution in the module is shown below. The following assumptions were made:

- Mounting surface is at -100°C [value chosen so three-digit output will report tenths of a degree]
- Conservative radiative cooling flux on CCD face = 1 * σ * (293^4 – 173^4) * (0.0634 * 0.0333 m^2) = 0.775 W/CCD, or 0.194 W for this quarter-section.
- 40 mW of amplifier power applied to a 1 mm^2 area in the corner of the sensor.

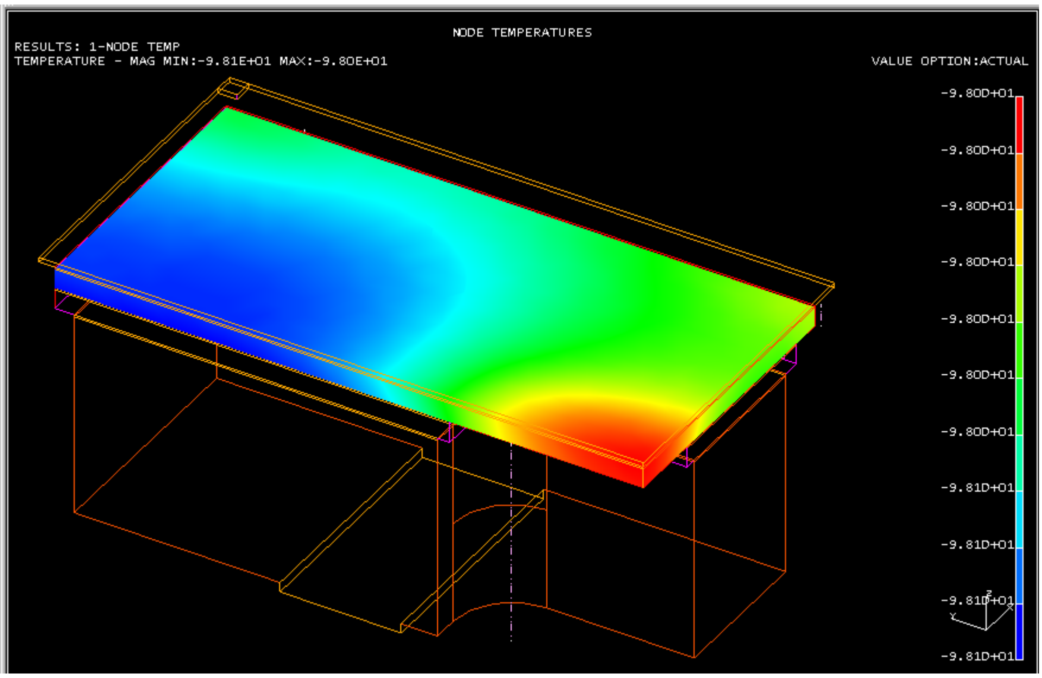
The FEA results are shown below. Note that the temperature within the Si and different AlN layers are very uniform but different, indicating that the low-conductivity epoxy is acting as a through-thickness thermal resistance, evening out the temperature within each of the other layers, which have much higher conductivities.



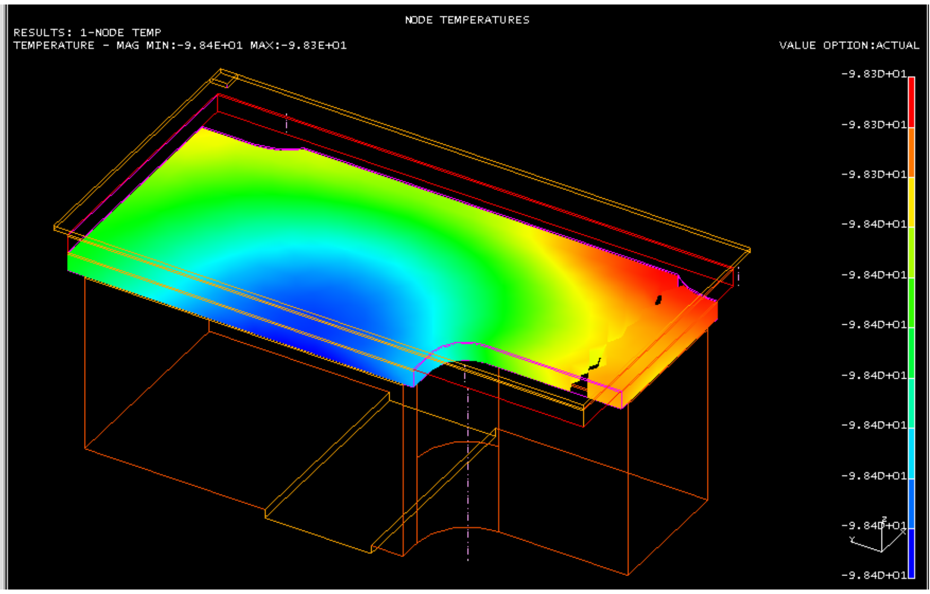
ΔT Between Si and Foot Boundary Condition = 2.3°C



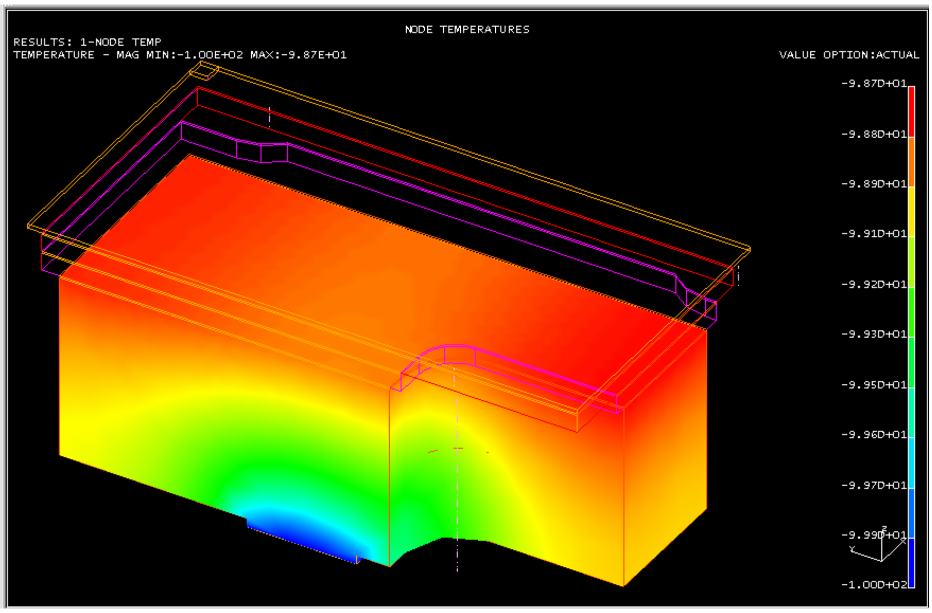
ΔT within the Si ~ 0.1°C (ignoring amplifier corner)



ΔT within the AlN Readout Board ~0°C



ΔT within the AlN Spacer ~ 0.1°C (visual break is a result of selection of two different volumes when displaying results)



ΔT within the Foot = 1.3°C

REFERENCES

1. MD-ENG-067, "Prototype Science CCD Module Design," by Greg Derylo, 1/20/05.
2. MD-ENG-103, "Cryogenic Mechanical Properties of Three Adhesives", by Herman Cease, 3/22/06.
3. MD-ENG-104, "Selection of an Epoxy to Bond Silicon to Aluminum Nitride", by Herman Cease, 3/26/06.

APPENDIX

ASSUMED MATERIAL PROPERTIES

Note that epoxy properties were determined from test data documented in MD-ENG-103 & -104.

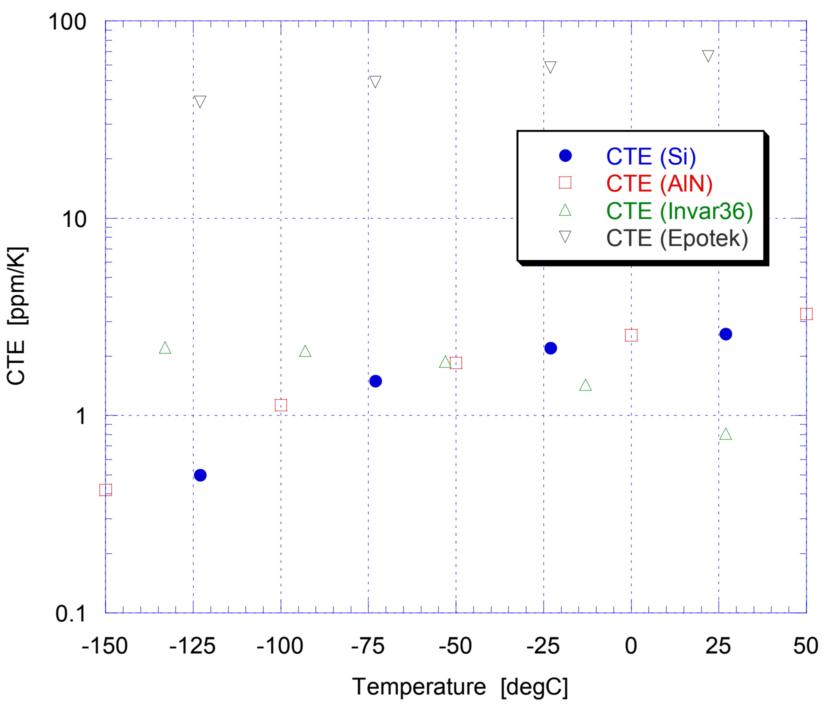
Modulus

Silicon:	131 GPa					
AlN:	275					
Invar36:	148					
Epotek 301-2:	Temp (degC):	-173	-123	-73	-23	23
	E (GPa):	6.99	5.74	4.47	4.11	3.66

Poisson Ratio

Silicon:	0.28
AlN:	0.22
Invar36:	0.31
Epotek 301-2:	0.35

CTE (See plot)



Stress Limit (MPa)

Silicon:	120
AlN:	2100 (compression) / 280 (tension)
Invar36:	483
Epotek 301-2:	Room temperature samples were tensile tested to failure at an average strength of 67 MPa. Five samples tested at 150K were subjected to a maximum stress of 44 MPa without failure, but the actual strength limit at cryogenic temperatures is not known. Test samples of AlN glued to molybdenum and thermal cycled to -100°C ten times showed no sign of damage [an FEA simulation of the sample predicted an 82 MPa maximum stress level in the epoxy (about 40 MPa away from the edge)], and over 50 pictureframe CCD modules (Si, AlN, & G10) tested to 175K or colder have experienced no failures.

Thermal Conductivity

Silicon:	See plot
AlN:	See plot
Invar36:	11 W/mK
Epotek 301-2:	0.16 W/mK